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AN INVESTIGATION OF THE APPLICABILITY OF DIVING TECHNIQUES TO SELECTED OFF-SHORE DRILLING AND PRODUCTION PROBLEMS

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AN INVESTIGATION OF THE APPLICABILITY OF DIVING TECHNIQUES TO SELECTED OFF-SHORE DRILLING AND PRODUCTION PROBLEMS

by

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ScB., United States Naval Academy, 1939

Submitted to the Graduate School of the University
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reqiurements for the degree of
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Thesis
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I. INTRODUCTION

A. Development of the Off-shore Problem

The petroleum industry has turned seaward in its search for more oil; oil, needed to meet the steady rise in the demand of our expanding economy; oil, needed for an adequate, ready, domestic reserve and; oil, essential to support that economy in the future, whatever it may hold. The success of this venture will mark the continuation of the contributions of this vigorous industry to the national destiny.

Off-shore locations have presented a more complex drilling and production problem than previous inland locations. The depth of water and the wide variation of water surface conditions have made the basic drilling requirement of no relative motion between the drilling rig and the well bore expensive to meet. The destructive power of ocean storm waves, winds, tides and currents has made drilling and production structures difficult and expensive to erect and maintain. Transportation and communication from shore to sea under even moderate sea conditions has not been easy.

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[1] References listed in the Bibliography

B. Purpose of Investigation

It is the purpose of this report to examine some of the present off-shore drilling and production problems in order to determine the applicability of certain diving techniques to their solution. No attempt has been made to present a detailed analysis of, or a complete solution to the problems discovered. No mechanical designs are presented. Instead, the paper shows the nature of certain difficulties and indicates the extent to which current diving techniques may contribute to their elimination.

Petroleum exploration parties and drilling crews have gone down to the sea in a variety of craft; some converted, some designed; in order to and explore and drill the contiental shelves. Costs have been high. Production has been difficult. It has been estimated that there has been little more than one dollar in income for every seven dollars spent.[1,2,3] The reduction of these costs was, is, and will be the problem of off-shore exploitation to be solved not only through the utilization of tested oil field science and methods, but also through the utilization of the seafaring skills and professions which in the earlier days, left a flavor of the sea in the language of the industry.[4] Certainly, the experience of the submariner and the diver may contain "know-how" useful in this off-shore venture.

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C. Statement of Procedure

The process of investigation has had necessarily two phases which may be stated as follows.

(a) the examination of current off-shore drilling problems; and

(b) the applicability of diving techniques to the solution of these problems.

The procedure followed during the execution of each phase of the investigation then fell into logical sequence:

Phase I

(a) examination of current off-shore drilling and production methods;

(b) identification of unique, off-shore drilling and production problems;

(c) identification of current applications of diving techniques to the solution of certain off-shore problems;

Phase II

(a) examination of current diving techniques and development;

(b) analysis of the potential extension of these techniques and developments to contribute to the solution of additional off-shore problems.

Pursuant to this purpose, it became apparent that the practicality of any potential contributions must be weighed in terms of the estimated costs for development, procurement and operation of any new or modified equipment against any advantages, immediate or future. Further, the costs should be balanced against the elements of risk from weather and from the nature of the operation. While these controlling factors are, in most cases, not susceptible to any exact evaluation, comparisons are possible. Marginal

features may be indicated.

The majority of terms used will be familiar because conventional terminology ~~language~~ has been used. However, in appendix I, there is a listing of terms and definitions. This should provide ready reference and preclude any misunderstanding of the terminology.

II. CURRENT OFF-SHORE DRILLING AND PRODUCTION METHODS

A. Drilling Methods

Current off-shore drilling methods may be divided into two classes by the manner in which the derrick is supported above the drilling location. In early off-shore development, the derrick was erected on a fixed, immobile platform, supported by pilings above the wave level. Currently, the method is still in use but is giving way to the mobile barge which not only supports the derrick but transports the drilling rig from one location to the next. Therefore, these classifications of off-shore drilling methods may be stated as follows:

(a) fixed platform;

(b) mobile barge.

1. Fixed Platform Method

Initially, fixed platforms were constructed to support the entire drilling rig, its accessories, and the drilling crews' quarters. One such platform alone cost the Humble Oil Company approximately one and one half million dollars. Fortunately, oil was found. Seven wells were drilled and produced from this platform.[5]

It was apparent that this high cost of a foundation platform was excessive for wildcat drilling.

A straight forward reduction of costs was apparent, if the size of the platform could be reduced without sacrificing the capability of drilling and producing several wells from the single platform. Further examination showed that salvability of platform structure would reduce costs by permitting reuse of material. In addition, important initial savings in time and material could be made, if major weight and load distribution changes could be

held within small limits.

More modern fixed platforms combine these ideas. Converted, government surplus, LSTs and other craft are used as tenders. These ships carry and power the main mud cir$\overset{c}{}$ulating pumps, the mud mixing and conditioning equipment, and the main mud tanks. They serve as floating storehouses for pipe, mud, water and equipment. Finally, they provide comfortable berthing and messing accommodations for the drilling crews. The multiple well derrick, an innovation of the Lee C. Moore Engineering Company, has a movable crown block and multiple power take-offs for the rotary table. This enables five wells to be drilled without shifting the derrick. In terms of platform design and construction this derrick has permitted the number of pilings per five-well platforms to be reduced from thirty-two to eighteen.[6] Sp.

Exact cost figures for this type of platform are not available but estimates run between two and three hundred thousand dollars.[7,8,9] This is still a considerable sum.

It should be noted that this platform cost reduction has not been realized without some disadvantages. These are: (a) mud pumps and circulating mud may be separated from the well during a heavy storm; (b) heavy duty moorings are required for the tender; (c) stand-by tugs are required for the tender during severe storm conditions or a certificated crew must be maintained on board the tender and (d) rather complex devices are required to permit movement of men and stores from the tender to the platform. In all fairness, it must also be stated that these devices permit the movement of men and stores under conditions of sea and weather which would preclude a similar movement from a small craft to the platform.[10]

2. Mobile Barge

When the costs of the fixed platform method of off-shore drilling

were appreciated, the advantages of a mobile, self-contained drilling craft were apparent. These advantages briefly are: decreased time to shift location; elimination of drilling platform costs; elimination of risks attendant upon moving heavy drilling machinery from a lighter to the drilling platform and the convenience of a compact, unitized drilling rig.[11]

The barges now in use may be subdivided into three rather distinct types which are:

(a) conventional ship or drydock which is limited in depth by its effective freeboard, usually to twenty feet of water or less in protected areas. Landing pontoons may be used to accomodate sloping bottoms and provide a level seat for the barge proper. Susceptibility to storm damage almost precludes the use of such equipment in open area.[12,13]

(b) fixed-leg, submersible barge which carries the drilling rig on a platform connected to the barge proper by steel legs. It may or may not have machinery compartments and storage tanks within the submersible barge hull. Its depth limitations are determined by the length of the legs. Present designs are limited to about fifty feet of water or less. External pontoons on outriggers, or special ballasting arrangements may be provided to accomodate a sloping bottom and to insure maintenance of vertical throughout the drilling operation.[14,15,16]

(c) Movable or adjustable leg barges which become drilling platforms upon reaching location by extending piles into, or pontoon based columns to the bottom and then jacking up the pile or column to a safe distance above the water level. For gulf areas, this level is now set at about forty feet above mean gulf level. Current designs are limited to approximately one hundred feet of water or less.[17,18,19]

It should be noted that, once these barges are drilling on location,

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they are effectively fixed platforms. In the cases of types (a), (b) and the pontoon based, adjustable leg barge, there is a possibility of coming out of the hole and moving the barge to a sheltered location in the advent of severe weather with adequate warning. Cost figures for the various mobile barges are not readily available. However, it is known that the Richardson and Bass drilling barge, "Blind Pass," a fixed leg barge, cost one and one-half million dollars without equipment.[20] A recent estimate for a similar barge equipped and with all auxiliary vessels was two million two hundred seventy-five thousand dollars.[21] The Ocean Drilling and Exploration Company's fixed leg barge with pontoon stabilizers for drilling in water to a depth of forty feet will cost in excess of three million two hundred thousand dollars.[22]

B. Production Methods

Current production methods closely parallel those methods used in drilling with the exception that platforms for well head controls need not be as large or substantial as drilling platforms. Every effort is made to centralize surface equipment in order that it may serve a maximum number of wells.

Service equipment may be installed on a conventional piling supported platform or it may be totally or partially installed on a submersible barge.[23]

The submersible barge production platform is similar to the fixed leg, mobile, drilling barge except that it does not require a complex ballasting or pontoon system.

Every effort is being made to eliminate manually operated controls at the individual wells and to substitute controls at the production platform or production platform controlled remote operating gear.

Any extensive maintenance requires the use of specially equipped workover barge.[24] Interruptions of work by weather conditions are not infrequent and are extremely expensive.

Any gas in excess of production requirements is generally flared unless the field is so fortunately situated as to permit a pipeline to a shore gathering system to be economically feasible.

C. Transportation Methods

The pipeline is the preferred method of transporting oil from the field to shore systems. The costs of these off-shore underwater pipelines are approximately three times the cost of similar land installations so that barges, both self or non-self propelled, are used extensively.[25,26]

Weather interruptions are a big factor in barge operations. Special fender pilings and moorings are required at the tank batteries. This combination of the interrelated factors of weather, mooring requirement, allowed production, and barge size has prevented the anticipated economies of barge transportation from being realised.

III. UNIQUE OFF-SHORE PROBLEMS

A. Common Drilling and Production Problems

Cost is the major ~~common~~ off-shore problem which has already been pin-pointed. However, it is understood that cost is the result of expensive solutions to the basic engineering problems involved. If less expensive methods are not developed, present costs could restrict the exploitation of off-shore areas to a fraction of the contiental shelf area.

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Another great imponderable in the off-shore venture is weather. It is freely and frequently granted that little or nothing can be done to control the weather directly. However, special Gulf forecasts predict its effect on operations in time to avoid some storm damage. Accurate statistical data are also compiled in order to build equipment to work in spite of the weather. These forecasts are eighty-five to ninety-five percent accurate for twenty-four hour forecasts and seventy-five to eighty-five percent accurate for periods up to forty-eight hours.[27]

Specifically, wave height and effective pressure are the two results or aspects of weather which control off-shore design and operation. For example, Gulf of Mexico experience shows that crew boats can only be safely and efficiently handled alongside a platform when wave heights are three feet or less or alongside a tender when heights are four feet or less.[28] All elements of the piling and piling bracing must be capable of withstanding storm wave action. Available figures for a wave of thirty feet in height above the ordinary high tide off the Texas Coast show the maximum dynamic pressure at the top of the wave to be seven hundred and thirty pounds per square inch.[29] After expensive experience during the October, 1949 hurricane design criteria were revised to the following:[30]

wind velocities, one hundred twenty-five miles per hour;

maximum wave height, forty feet;

storm tide, ten feet above normal high tide.

Even these figures require the acceptance of the risk that storms of long duration, capable of destroying the structure, may occur once every forty or fifty years.

Any improvements in the present forecasting or design data can only be made after a considerable period of time and research.

Current equipment in operation or under construction is limited to water depths of less than one hundred feet.[31] However, there is reason to believe that oil will be found in sediments out to six hundred feet of water.[32] Constant attention and design study is being devoted to the problem of eliminating this depth limitation of present equipment in order to permit exploitation to the one hundred fathom (six hundred foot) curve.

Mobility is another desirable characteristic of off-shore equipment. Mobile equipment will be largely salvable and capable of reuse, and will reduce costs incident to moving from one location to the next. In certain locations, equipment may be used which is susceptible to storm damage on location but which may be moved to a sheltered location at the onset of dangerous weather. A survey of eighteen oil companies and ten designers or constructors of off-shore equipment[33] showed the following desired characteristics which affect mobility:

(a) shallow water unit

operating depths - ten to forty feet;

capable of shifting locations in one day;

capable of being towed at three miles per hour against four foot waves;

(b) deep water unit

operating depths - fifteen to one hundred feet;
capable of shifting locations in three days;
capable of being towed at five miles per hour against five foot waves.

Production and drilling platform designs have the common requirements of adequate strength to perform their function in adverse weather, maximum savability, ease of erection, and low initial costs. Although mobile drilling barges may be the best answer to the drilling phase of the problem, platform design requirements must be met in production. Current thought,[34] expressed by Dale F. Leipper, is as follows: "It was brought out that there are two ways in which off-shore structures may be altered to withstand the damaging effect of hurricane waves:

(a) strengthen the structure or reduce its wave resistance;

(b) raise the platform above the zone of wave resistance."

It should be noted that this approach will raise initial costs, if nothing else.

Support of the drilling and the production operation is another expensive and perplexing phase of the whole problem because we are again face to face with an implacable adversary, the weather. Recently, helicopters have been brought into use for the transportation of men and light materials but the movement of heavy equipment and the erection of off-shore structure still wait upon the whims of the elements. Wave heights of greater than six feet stop platform building. The driving of conductor pipe is stopped by waves greater than four feet.[35,36] The initial off-shore test off Mustang Island by the Gulf Oil Company was delayed for about ninety days with equipment demurrage estimated at a rate of four thousand five hundred dollars per day.[37]

Polution of inland waters or of the shores of water front property is a problem in the mental foreground of any person connected with off-shore oil. Fortunately, good pressure control is possible. The consequences of any casualty, such as a well "blowing wild," would be extremely expensive not only in terms of damaged equipment but more so, in terms of property damages and lawyer's fees.[38]

B. Operational Problems While Drilling

The problems incident to the actual drilling off-shore are not any greater than those encountered in the Gulf Tidelands. Somewhat elaborate precautions are taken to control high pressure fluids. At moderate depths three blow-out preventers are employed. An additional preventer is added for deep drilling. One operator is reported to have five preventers in use. Mud quality control is essential. Ample supplies of make-up material are carried.[39] In addition, it is important in off-shore drilling to insure that the conductor pipe is deep enough to preclude undermining any portion of the foundation, be it a piling or a submersible barge.

Any operator, requiring continuous service from a drilling tender, immediately finds that the mooring plan for the tender requires close inspection. In even moderate seas, surging of the tender against the drilling platform can be destructive. Essentially, the bow or stern of the tender must be fixed in position, regardless of possible wind and tide combination. This requires that any mooring gear hold without dragging or failure. During severe storm conditions the tender must be removed to shelter or allowed to swing clear of the drilling platform to a position where a long scope of chain may be used and sea room is available. Similarly, the platform must have emergency power for mud pumps, and a mud supply or allow time to come out of the hole and batten down with each warning of dangerous weather.

C. Production Problems

Production shares the problem of platform design with drilling. In addition, it has a problem in maintenance because production platforms are in use for a long period of time. Similarly, weather is not only an element of destruction but also the drawback to transportation. Seas with waves greater than four feet make access to the platforms dangerous and preclude the safe conduct of loading from the platform to a barge or cargo lugger. Therefore, pipeline transportation of crude to shore is preferred~~,~~ where it is practicable.

However, the maintenance of these pipelines is a problem which can be compounded by a location remote from ports and by weather. For example, there are nineteen miles of submerged pipeline between Hollover Field and the beach. Repair equipment must travel approximately one hundred and fifty miles, when needed. Repair equipment rentals run from one to three and one half thousand dollars per day of the total. A breakdown of repair bills show ninety percent of the total for travel and stand-by time, and ten percent for actual work.[40]

Gas production from off-shore fields is still not economically sound in most cases. Only four of twelve off-shore gas fields are producing. The remainder are shut-in.[41]

IV. SUMMARY OF CURRENT DIVING TECHNIQUES

A. Submarine Medicine

Any appreciation of current diving applications and techniques must be accompanied by a rudimentary knowledge of the effect on man, when he breathes various gas mixtures under changing pressure conditions. Such knowledge by no means embraces the entire field of sumbarine medicine but is included therein. The following discussion is not complete. It is intended to pinpoint those limitations of man which also limit the period he can work underwater.

1. Bends or Caisson Disease[43]

For purposes of this discussion air will be considered a two gas mixture of oxygen and nitrogen. At atmospheric pressure each person has dissolved within his blood stream and within his body's tissue a quantity of the inert gas; in this case, nitrogen. If the air pressure of the inhaled air is increased, as it is as a man dives or enters a caisson, a greater quantity of nitrogen or inert gas is taken into solution by the blood and tissues. If the pressure of the inhaled air is decreased, a quantity of nitrogen will be slowly eliminated from the blood and tissues into the expired breath via the lungs. As long as this elimination process is gradual, no adverse effects occur. However, if the decrease in pressure is rapid, the inert gas will leave solution and form bubbles before it is transported by the blood stream to the lungs. These bubbles press upon the nerves and produce a symptom which varies from a slight itching to severe pain; generally noticed near the joints. This is known as caisson disease, or bends. In severe cases these bubbles can cause permanent injury to the nervous system.

It should be noted that the quantity of nitrogen taken into solution

varies with the pressure of the inhaled air and with the duration of exposure to that pressure. Therefore, a record of the pressure and the time of exposure is necessary in order to determine the time rate of pressure decrease which will allow this nitrogen or inert gas to be safely cleared from the body.

It is also logical and correct to assume that, if another inert gas, such as helium, were substituted for nitrogen, a different, safe, permissible rate of pressure decrease will govern. Therefore, it follows that "bends" is not caused by nitrogen alone but will be caused by any inert gas.

Helium is the inert gas commonly used in artificial breathing mixtures. Generally, it may be stated that helium will diffuse through the blood stream more rapidly but will not enter the body tissues as rapidly or readily as will nitrogen. Therefore, helium-oxygen mixtures will allow a greater rate of pressure decrease than will compressed air. It should be noted that helium oxygen mixtures do not provide any insurance against "bends" but on the contrary, they are more sensitive to the rate of pressure decrease. This property of helium, which allows a quicker purging of gas from the blood stream and body via the lungs, is only one of the advantages gained by its use.

Practically, tables[14] are available for compressed air and for various helium-oxygen mixtures which show or, in the case of helium-oxygen, permit the computation of the time to be spent at selected lower pressures (decompression time) when the greatest pressure (depth of dive) and the interval in minutes between the time of leaving the surface to the time of leaving the bottom (time on bottom) are known. This table for compressed air shows that a dive to one hundred feet and a time on bottom of eighty-five minutes requires approximately sixty-one minutes of decompression time. A dive to two hundred and fifty feet on air and a time on bottom of twenty-five minutes

requires a decompression time of approximately two hours and thirty minutes.

Finally, it should be understood that these decompression tables are the result of practical experiments, using numbers of well-conditioned men as subjects. The decompression schedules, even when religiously followed, will protect only ninety percent of the men after heavy, working dives.

2. Narcotic Effect of Nitrogen[45,46]

When the body is exposed to pressures of four atmospheres (absolute) or higher, the nitrogen present in the inspired air induces a narcotic effect which may be compared to alcoholic intoxication. Unfortunately, the responses of the individual are similar to those of a person not receiving a sufficient amount of oxygen. The variation between individuals, when exposed to nitrogen narcosis, is wide.[47] In 1915, incident to the salvage of the USS F-4 off Honolulu, divers worked at a depth of three hundred four feet (approximately nine and a quarter atmospheres, absolute).

Helium, however, does not produce this narcotic effect. Use of helium-oxygen mixtures permit Ⓐ diving to depths of five hundred fifty feet < without adverse effects.[48,49]

3. Anoxia and Oxygen Poisoning[50,51]

Anoxia, the lack of an adequate supply of oxygen, has been mentioned previously. It produces symptoms similar to nitrogen narcosis. Therefore, at depths below one hundred fifty feet only the experienced, compressed air worker or diver will be able to distinguish anoxia from narcosis. It may be concluded that the worker or diver is dependent upon his equipment and his tender, if any, for an adequate supply of oxygen.

When an individual breathes pure oxygen under pressures greater than one atmosphere, absolute, he may, after a time, experience symptoms which vary from numbness or dizziness to a convulsive seizure. These symptoms of

oxygen poisoning have an irregular and wide occurence pattern even for a single person. Not very much definite information is available concerning the reasons for, or the mechanism of, this poisoning. Dr. C. J. Lambertsen, School of Pharmacology, University of Pennsylvania; the U. S. Naval Medical Research Unit, Bethesda, Maryland and the U. S. Naval Experimental Diving Institute, Washington, D. C. are now conducting or have conducted investigations into various phases of the problem. It is known that apprehension, hard work or carbon dioxide concentrations in the inspired gas mixture will accelerate occurence of poisoning symptoms. There is reasonable assurance from diving records that there is no danger of oxygen poisoning when breathing compressed air, although symptoms may have been masked or not reported. Oxygen poisoning may occur when breathing compressed gas mixtures which are richer in oxygen than air. In using helium-oxygen mixtures for deep diving, the partial pressure of oxygen is always maintaned below 2.3 atmospheres, absolute. This arbitaary rule has been successful in practice.

From the foregoing, it may be concluded that the useful time on the bottom for any dive will depend upon the inert gas present and the partial pressure of that inert gas when on the bottom. The partial pressure of the inert gas may not be lowered indiscriminately by use of oxygen rich mixtures without danger of oxygen poisoning.[52]

h. Carbon Dioxide Poisoning.

On the surface, a three percent concentration of carbon dioxide is approximately the maximum which can be tolerated without distress, accompanied by heavy breathing and headache. For this reason and to avoid the accelerating effect that carbon dioxide concentrations have on oxygen poisoning, it is important that the partial pressure of any carbon dioxide in the inspired gas mixture be less than forty-four hundreths of a pound per square inch (0.44 psi equivalent to the partial pressure at surface of 3% CO_2).

In conclusion, it may be said that the medical knowledge of man's response to various gas mixtures, when they are at a pressure greater than one atmosphere, is barely sufficient to permit the current types of diving. There is no evidence to demonstrate the effect on man, if other gases, such as those associated with crude oil, were inhaled under pressure. Current research in this field may enhance our understanding of oxygen poisoning and bends but it is doubted that any immediate results will greatly increase the time on the bottom at depths greater than three hundred feet.

B. Hose Diving[53]

As the name indicates, a hose diver is connected to a surface breathing gas supply by means of a hose. The diver may wear a shallow water helmet, a face mask, a light weight diving dress, or the conventional, complete diving dress depending upon the temperature of the water, the depth, and the nature of the work to be accomplished. In cold water, for deep dives, or for heavy work around obstructions, an appropriate diving dress will be used for protection. For working dives to depths greater than one hundred fifty to two hundred feet, where the advantages of the helium-oxygen mixtures are appreciable, a complete diving dress with a special helmet must be worn. It will suffice for the purpose of this investigation to state that the helmet for use of helium-oxygen mixtures has an attached carbon dioxide absorbing canister to insure a low concentration of carbon dioxide in the inspired air and to economize on gas usage.

In addition to the depth and time on bottom limitations, which have been discussed, the diver's ability to work will be limited by: currents, water temperatures, and the turbidity of the water at his working depth. Currents above a velocity of one knot are a real problem to the diver. For deep dives even this velocity, if consistent in direction, could make diving operations impossible. Cold water conditions may be corrected by use of the diving dress and heated underwear, except when the work requires a high degree of finger dexterity. In a few areas, high water temperatures have been a problem which was successfully met by endurance and a shortened working period. Turbid conditions at the working depth limit the vision of the diver, even when artifical lighting is used. However, if the nature of the work and the water temperatures permit, the diver can work by sense of touch

alone. It should be noted that a diver, walking on a muddy bottom, will create enough disturbance to impede his vision.

In conclusion, it is stated that although the hose diver has an advantage of increased time on the bottom, he is also restricted by current conditions and by any disturbance he may create on the bottom.

C. Free Diving

There has been considerable attention given to this type of diving in current literature and magazines. Here again, as the name implies, free diving is diving without any connection to the surface or dependence upon an air hose. Naturally, diving in this manner has attraction for the underwater sight-seer and the spear fisherman.

A free diver is subject to all of the medical limitations of the hose diver and, in addition, is limited by the volume and pressure of his breathing gas mixture and by his rate of consumption of that supply. It may be added that, when work is related to breathing gas consumption, tests performed at the Experimental Diving Unit and elsewhere, have demonstrated that swimming is the hardest work man performs underwater.

Training in the use of free diving equipment is deceptively easy. As a group of West Coast divers have stated, "In five minutes a man can learn enough to be able to kill himself."[54] An outline of a training schedule for the use of free diving equipment is contained in National Academy of Sciences Publication, 274, entitled "On Using Self-contained Underwater Breathing Apparatus."[55]

The practical advantages and limitations of the free diving technique are: the ability to operate in higher current velocities than a hose diver when searching and when doing light work; the equipment is less expensive; the equipment is more mobile; the free diver causes less bottom disturbance; the free diver requires less surface support; and the free diver may employ underwater vehicles.

In conclusion, it may be stated that free diving is complementary to hose diving within the depth limitations of the free diving equipment used.

D. The Caisson and Diving Bell

The caisson and the diving bell are familiar equipment to underwater constructors. They both utilize a closed, underwater chamber from which the water is excluded by air pressure in order to permit men to work on the bottom within the chamber. The caisson is a cylindrical structure extending to the surface so that access to the pressure chamber may be effected by an air lock. In the usual employment of the diving bell, the men within the open bottomed chamber or bell are lowered and raised by a hoist from a surface vessel. There are some installations, where the diving bell is semi-permanently sited under water and used as an observation station. In this case, the observers must dive from the surface and enter the bell from the bottom.

Men working in a caisson or diving bell are subject to all of the medical limitations of a diver. However, this equipment has the advantage of permitting work by men who are unencumbered by diving gear, who are warm, and whose vision is unimpaired by the turbidity of the water.

E. The Diving Vehicle

Excluding the submarine, the bathysphere, and the bathyscaphe, there is another fairly new group of diving vehicles which are not pressure tight. They are designed for use by the free diver in order to permit him to increase his range under water by substituting a motor or bicycle-driven propeller for swim fins. An average, well-conditioned, man can swim with fins about one mile underwater, whereas, in a diving vehicle, he can operate for a distance of about four miles.[56]

These craft have been used to a limited extent for recreation and underwater photography. Their possible advantages have not been exploited industrially.

F. Diving Tools

There is a rather common opinion which is inherited from stories of early salvage operations and which classifies the diver as a species of underwater rigger. Allegedly, he can, with expert guidance from above, find things underwater and attach lines to his discovery.

Actually, the present day diver is a versatile mechanic.[57] He is capable of cutting with gas or electric arc, of welding, of caulking, and of setting explosive charges. Virtually, all of the air operated or explosive operated hand tools may be adapted for the diver's use. The pontoon and the lifting bag provide him with independent and powerful hoisting equipment; albeit his control is somewhat rudimentary.

Recently, two other devices have been tailored for underwater use. These are the camera and the industrial television chain.[58] With this equipment it is possible to see, record and interpret information which the diver might have missed because of limited vision, fatigue, nitrogen narcosis, or lack of special competence. Both the camera and television chain are limited by turbidity, just as is the diver. Good conditions may give results at fifty feet, but more often less than ten feet is the useful range. In slit laden water, no picture~~s~~ or vision is possible unless a non-turbid substance is used to displace the water between the lens and the object to be viewed or photographed. This technique is experimental.

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G. Current Applications of Diving Techniques

Diving techniques have already been utilized by petroleum geologists, pipeline constructors, and platform erection crews. The geologists have utilized the technique of free diving as a means of extending their surface map under water.[59,60] The diving bell has also been used to obtain gravity meter readings on the ocean floor.[61] The pipeline constructor has employed the diver to probe the bottom prior to explosive ditching, to inspect the bottom or ditch prior to pulling the explosive string or pipe, and to walk the pipe to insure that it is sufficiently deep in the ditch. Divers also assist in ditching, and placing the pipe string.[62] The platform constructor has used the diver to weld split collars to the platform piling. This permits pre-stressed wire braces to be strung from the mud level to the piling cap.[63] In general, these are the traditional tasks of the diver as an auxiliary to under water construction.

V. ANALYSIS OF POTENTIAL DIVING APPLICATIONS

A. Submerged Drilling

The practical difficulties of working under pressures greater than one atmosphere have prejudiced any consideration of submerged drilling. However, a statement in the March issue of World Oil reads, "Within five years diving bells capable of being submerged below water and fully equipped for drilling and with crew quarters, may be a reality."[64] This was encouragement enough to prompt a reexamination of the potential of this approach to off-shore drilling.

1. Requirements

If the problems subsequent to completion; such as control, routine maintenance and work-over; are divorced from the picture, the total potential of submerged drilling can be assayed by considering in some detail the requirements of such an operation. In this consideration, the following statement was used for guidance, "Although open-water drilling may eventually require radical changes in drilling equipment, the changes should be gradual. Attention first must be given to the development of smaller items of equipment and techniques required for the specific problems of water operations."[65] It was also assumed that any project of this magnitude would strive to eliminate any depth limitations; that is, provide for a six hundred foot operating depth. In addition, the deep water drilling unit should permit unrestricted, year-round drilling.[66]

In general terms, the requirements for drilling may be listed as follows: (a) transportation or logistic support, (b) a source of power, (c) a derrick and hoisting gear or its equivalent, (d) a mud system, (e) a drilling string,[67] (f) storage facilities, and (g) messing and berthing facilities.

The transportation of the submergible drilling barge, and its logistic support while it is "making hole," poses no new problems. The barge will either be towed to location or be self-propelled. In as much as propulsion equipment adds to the complexity of the barge and to the payroll, it is assumed that a non-self-propelled barge would be selected. Logistic support would require one tender or station vessel to assist in emergencies and to serve as a warning ship for other surface craft. Another cargo lugger and probably a helicopter would be required for transportation of men and materials from the shore base of support to the tender.

Transfer of men and material from the tender to the submerged barge would undoubtably be restricted to emergency requirements. However, such a provision would be mandatory to bolster the morale of the barge crew, to obtain reasonable insurance rates, and to provide for the technical services, such as electric logging and cementing. This transfer could be provided for in any of three ways: (a) by means of a rescue chamber similar to the device employed by the Navy to rescue the survivors of the Squalus;[68] (b) by a snorkle enlarged and fitted to permit access; and (c) by either (a) or (b) above for personnel and small equipment only, plus a cargo lock into the diving bell section of the barge which would permit a diver to rig cargo in and out. After consideration of the magnitude of this venture and of its experimental aspects, the third way is the logical selection. However, prudence dictates that both the access snorkle and the rescue chamber be provided.

Power could be provided by diesel electric generators installed in the submerged barge. Stand-by power for emergency surfacing and for ship's service, only, would be provided by batteries. It should be noted that the diesel exhaust blower discharge pressure must be in excess of three hundred pounds per square inch. (This assumes a six hundred foot operating depth, a ten foot storm tide, a forty foot wave allowance and a sea water pressure

gradient of .445 psi. per foot.), if a submerged exhauste is contemplated. This presents a strong reason for discharging exhaust gas through the snorkle and accepting the additonal air conditioning load.

At this stage, it seems appropriate to pinpoint the characteristics required of the snorkle:

(a) be fitted for emergency access by men;

(b) provide a conduit for intake air, exhaust, and mud tank vents;

(c) be of sufficient height to provide for an operating depth of six hundred feet, which height would be approximately six hundred fifty feet;

(d) possess sufficient mechanical strength to withstand hurricane wind and wave loading, which would be in excess of eight hundred forty-seven pounds per square inch. Exact values for this storm load are unavailable.[69]

(e) require sufficient internal or external bracing to resist the toppling movement of wind and wave loading.

Now, the decision to provide an independent power supply for the submerged barge appears to be questionable. The alternative to this approach is to supply power and air from the station vessel. The requirement for an air source could be eliminated, if information concerning the effect on man of protracted exposure to abnormal concentrations of carbon dioxide and concerning the design of carbon dioxide air scrubbers, were freely available. Nevertheless, the mooring plan for the tender requires close scrutiny because any occurence which would require the tender to slip its moorings would interrupt drilling operations. The submerged barge would be forced to operate on emergency, battery power and on air from its banks.

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Here again it is advisable to pin point the characteristics of the tender moorings:

(a) each leg must have sufficient weight, strength, scope and holding power to hold the tender without dragging under hurricane wind and wave conditions;

(b) the movement of the tender must be controlled by the mooring within the limits of the electric power transmission cable length and strength;

(c) each leg must be sited so as to preclude the possibility of fouling the electric cable or the submerged barge;

(d) it must permit the ship to ride in such a manner as to minimize storm damage.

It is not considered that atomic power will be available for general use. If available, it should be considered.

The derrick and hoisting gear, or its equivalent, would be housed within the diving bell structure where the gas pressure would be equal to the barge depth. The limitations to a man's ability to work in pressures greater than one atmosphere dictate that the rig be controlled from locations not subject to increased pressure. This would include remote control for setting casing, cementing and logging as well as normal drilling. Any person entering the bell proper must be supplied with a special breathing gas mixture. Decompression routines must be religiously observed. All connections through the bell body must be provided with stuffing boxes and be properly packed. It will suffice to note that adequate provision must be made to control and release high pressure gases which could blow from the hole. An elaborate system for the detection of explosive mixtures and purging these mixtures from the bell is a correlated requirement.

equivalent to the pressure of Open Sea. in salt.

The mud system must be completely closed in order to prevent the contamination of the barge air. This requires that the shale shaker and the the mud tanks be vented to the ocean or vented through the snorkle with the

diesel exhaust. Similarly, lubricators will be required on all sampling connections.

The drilling string design would be governed by the type of remote operating gear employed. The perfection of the turbo-drill would simplify this problem somewhat.

Storage facilities for that material not required in drilling or for the drilling material which may be piped into the bell present no unusual problem. However, storage for the drill pipe and collars, the casing, and the production tubing must be directly accessible to the bell structure.

The design of berthing and messing facilities for the drilling crew would present no new problem in submarine design. Air conditioning would be mandatory.

2. Advantages

The advantages of submerged drilling may be stated as follows:

(a) freedom from weather interference;

(b) access to the entire contiental shelf.

3. Current Drawbacks

The obstacles in the path of a submerged drilling barge development are considerable. The engineering development of the barge design alone is a major undertaking. Other foreseeable problems are: the design of an adequate snorkle which will not dangerously impair the barge stability while submerging; the design of the bell structure, including or replacing the derrick; or the design of an adequate tender mooring plan. In addition, the requirement for complete remote control of the drilling processes indicates that an extensive, added development of current automatic drilling machinery is essential to the success of the entire project. This further development must include the discovery of new techniques for the control of cementing,

logging, running of casing, and well completion. Medical research data are not generally available to provide the design criteria for an adequate air purifying system. The selection and training of the drilling crew would be expensive and time consuming. Most stringent safety procedures would be a necessity. The initial cost of the barge alone would be at least ten times that of current equipment or over thirty million dollars.

lengthy, results of testing, and test procedures. Typical numbers here are not presently available to provide the design engineer for an adequate and justifying system. The selection and operation of the optimum type would be dependent on time constraints. Full equipment cycling procedures would be a necessity. The initial cost of the entire system would be at least ten times that of current equipment in other similar systems.

B. Platform Construction

Diving techniques offer no great contribution to the current methods of platform construction. Prior to the advent of the small platform and the drilling tender, the use pf prefabricated, submerged storage tanks for mud, fuel and water presented attractive advantages, particularly, in lowering the center of gravity and saving platform space.

C. Submerged Production

Submerged production from off-shore wells also presents practical difficulties. However, these difficulties are mitigated by the fact the production operations performed at the well head are considerably less complex, mechanically, than are the various operations performed during drilling, if a permanent type completion was were made. Therefore, workovers do not require large, bulky equipment compared to the drilling rig. Another, favorable factor is the fact that workover operations are of relatively short duration and may be scheduled during periods of favorable weather. ←

1. Requirements

The mechanical requirements for working over permanently completed wells are:[70] (a) accessibility for installation of the wire line blowout preventer, of a lubricator with a wire line stuffing box, or the cementing head; (b) hoisting gear to assist in the installation of the above equipment; (c) wire line and reel for running tools in and out of the well; and (d) the ability to determine the tool location by the feel of the wire line.

The factors which will control the accessibility of the well to a diver are depth, turbidity of the water, and the water temperature. Depths to one hundred fifty feet are accessible to divers breathing compressed air for periods of time sufficient to install equipment. A small decompression chamber on the workover boat can be used to advantage by replacing the ten foot decompression stop or by using surface decompression exclusively. Briefly, decompression time on the stage may be cut approximately fifty percent by using the chamber for the ten foot stop. Turbid water should not be a critical condition to the experienced diver but it will slow him up. Water temperatures within the Gulf of Mexico should present no problem to the diver.

Temperatures elsewhere may slow operations.

The hoisting gear for handling equipment to be installed at the well head would require design and development. In addition to the boom, plumbing the well head, it should have an air driven winch with a reel capacity of about two hundred feet of wire. Preferably, this gear would be unitized. The running end of the winch wire should not only be fitted to handle the equipment for the well head but should also handle a Navy-type, carpenter stopper.

The wire line and reel for running tools in and out would be installed on the tender. The wire line should lead through a dead sheave to provide some freedom of motion for the tender. This line from the boat would be stoppered off and the tools handled by the diver's winch at the critical points; i.e. the top of the hole and the seating locations in the production zone. It should be noted that this procedure will give the diver the ability to feel the line.

Well control equipment presently in use could be converted for use on submerged wells without any major redesign. Hydraulic equipment would prevent only a slightly different corrosion problem. Electric equipment would share the corrosion problem and, in addition, require pressure proofing. This could readily be accomplished by a hydraulic fill or by the installation of a gas pressured shell.

2. Potential Advantages

The potential advantages of submerged completion are as follows: (a) elimination of well head production platforms and their maintanence and (b) elimination of weather and fire hazard to well head platforms and to the well head tubing between the bottom and the platform.

3. Disadvantages

The disadvantages of this submerged procedure are: (a) increased

complexity of workover procedures; (b) higher workover costs and (c) increased cost of pressure proof well head controls.

4. Summary on Submerged Production Application

It should be noted that gathering tanks and other related service equipment will still require platforms. Therefore, submerged completions will only be advantageous for those wells which are too remote to permit completion at the gathering tank platform.

VI. CONCLUSIONS

As a result of this investigation, it is possible to draw some conclusions concerning the prospects of applying diving techniques to the offshore problems. At this moment, it is apparent that divers can only perform their traditional services in platform construction, in underwater inspections, and in pipeline repairs. Aided by some engineering development of equipment and techniques, submerged, permanent completions to a depth of about one hundred fifty feet could be serviced by employing diving techniques. The development of an all-weather, deep water, submerged drilling rig is a research development problem involving more than the barge development alone. Even after the difficulties related to the power supply, the bell design, and the accessibility of the barge are eliminated, more basic obstacles remain. The basic data which are required in order to establish design criteria for the barge ventilation system and air purifying are unavailable. Automatic drilling rig controls which permit remote control of the essential operations of running casing, logging, and cementing have not been developed. The techniques for completing and producing a well at the greater depths (beyond one hundred feet) are untried. The availability of a crew capable of operating and maintaining a submerged drilling rig is uncertain.

VII. RECOMMENDATIONS

Therefore, it is recommended that :

(a) the development of submerged production be initiated and pursued with the purpose of demonstrating economic as well as technical feasibility;

(b) a liaison be established with the U. S. Navy, Bureau of Medicine and Surgery, in order to secure the release of data which are required to establish design criteria for the ventilation system of any submerged, inhabited barge;

(c) that the development of automatic drilling rigs be continued and their functions expanded to the control of running casing, cementing, and logging;

(d) no direct engineering development of a submerged drilling barge be initiated until design criteria on ventilation and on the drilling machinery are available and are firm.

APPENDIX I

Definitions

Bathyscaphe - A small submarine having gasoline instead of air for main ballast control. It now holds the world's record for deep diving. It is used by J. Costeau and A. Picard.

Bathysphere - An observation chamber, fitted to withstand great pressures, which is lowered to great depths. It has been employed by William Beebe and Auguste Picard.

Blowing wild - An expression for an oil well which is out of control and violently emitting oil and gas.

Carpenter stopper - A mechanical device for holding a wire line by means of opposed wedges. The Navy-type stopper will hold the wire until it parts, without damage to the wire.

Cementing - A name given to several similar operations whereby cement is injected into a well in order to seal the ends of the casing to the surrounding formation; to repair a casing leak; or to isolate a particular strata behind the casing string for production.

Conductor pipe - A relatively short large diameter pipe extending from the surface and used to provide a passage for the drilling fluid at the start of drilling.

Crown block - The fixed block of the hoisting tackle of an oil well derrick.

Decompression time - The total time required to safely reduce the gas saturation of a man's body to normal, after exposure to pressures greater than one atmosphere.

Drilling string - The rotating elements of the rotary rig from the swivel to the bit.

Logging - A general term including any method of securing information concerning an oil well which may require lowering instruments into the well bore.

Lubricator - A mechanical device permitting the introduction of tools or equipment into a high pressure vessel or pipe without release of pressure.

Making hold - A term applied to a drilling rig which is on location and engaged in drilling.

Mooring - A term used here to describe the entire arrangement for attaching a vessel to the ocean bottom.

Mud - A descriptive term for the fluid used in drilling by the rotary method and for any dry or concentrated liquid form of that fluid.

Off-shore - A term used here to designate any area which is directly exposed to the open ocean from the lower low water mark to the one hundred fathom curve.

Pontoon - A chamber which is fitted with special ballasting and deballasting equipment and commonly used to assist in raising objects from the ocean floor. It is here used to include any tank, not included within the hull proper but attached to the hull and used for adjusting the bouyancy or bearing pressure of the hull on the ocean bottom.

Running end - The moving or free end of a working rope or line.

Stage or stop - An intermediate pressure between the working pressure of the diver and atmospheric pressure at which the diver must remain for a fixed period of time for safe decompression.

Tidelands (as used herein) - Any land which underlies water which exhibits tidal action.

Turbo-drill - A drill and attached turbine used in connection with a rotary drilling rig whereby the turbine and drill are rotated by energy transmitted by the circulating fluid (mud).

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